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Wind Tunnel Test Results for Gas Flows inside Axisymmetric Cavities on Cylindrical Bodies with Nose Cones

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I. ABSTRACT

Experimental test results of air flow inside and at the cylindrical cavity located on axisymmetric body are presented. These tests were conducted in the wind tunnel A-7 of Institute of Mechanics at Moscow State University. Pressure distribution along the cavities and optical measurements were obtained. Dependence of these characteristics of length of a cavity in the range: L/D = 0.5 - 14 and free stream Mach in the range: M_∞ = 0.6 - 3.0 was determined. Flow structure inside the cavity, cause of flow regime change, separation zones geometry and others were studied. In particular, the flow modes of with open and closed separation zones are determined.

II. INTRODUCTION

Cavity flow (cutting, dredging) is typical example of the separate flow what appears in a great number of applied problems including flying devices (devise accommodation, wheel niches, conjugation of rocket blocks), wind tunnels and various elements of technological installations.

A number of the theoretical and experimental researches devoted to study of the cavity flows is published. This studies are conducted in a wide range of free stream velocities, from an incompressible liquid low speed flows up to hypersonic gas flows with high Mach number. These studies can be conditionally divided onto two directions: 1) investigations of average flows in time currents inside cavities, and 2) investigations of pressure pulsations and acoustic processes. With the size paper limitation, we will consider only references which are devoted to experimental investigation of average in time gas flows (in the chronological order), and also the data what will be used for comparison with the present experimental results.

The first experimental test results of gas flow inside the rectangular cavity formed by a low speed free stream was published in [1]. The 2D and axisymmetric models of cavities were investigated at Mach number, M_∞ = 2.78; the boundary layer was turbulent, the ratio of boundary layer thickness to the cavity height, $\delta / D = 0.44$ [2]. Note,

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that, mainly, these results are concerned to study of the flow separation and heat exchange. There are experimental test results for separate flows that are formed by the flow at the step or cavity [3], and also for average time characteristics of the flow and those of heat transfer at a hypersonic turbulent flow [4]. Influence of the cavity size and of Reynolds number at the hypersonic flow with Mach number, M=7.3, around axisymmetric bodies on the time average of values of pressure, thermal fluxes and temperatures are experimentally investigated in [5]. The flow of a viscous incompressible fluid in the cavity with the square cross section is experimentally studied in [6]. It is established, that a nucleus is formed in the cavity with constant vorticity, and secondary whirlwinds are formed in corners.

The characteristics of separate ground flows, including flows between bodies, are considered in [7]. The known review of works on separate gas flows [8] contains the description of some research of a cavity flows. The structure of a cavity flow, formed by supersonic co-flow of gas, is considered in [9]. The characteristics of liquid flow in flat rectangular cavities in a range of Reynolds number, Re=500-5000 are measured in [10]. In this case the secondary flows in front ends are discovered in the flat vortical cavity flow and Taylor-Görtler vortexes are developed along the cavity walls. Incompressible liquid flow in small depth and large depth cavities with rectangular cross section was investigated with the help of Doppler laser, a speed measuring instrument [11]. Experiments were carried out with the laminar flow regime in front of a cavity. It is established, that in a deep cavity two elliptic whirlwinds exist (the top one and the bottom one), rotating in opposite directions.

Measurements of pressure and visualization of a flow for the cascade of the square cavities located on identical distance from each other at Mach number, M = 1.5, 2.5, 3.5 were carried out in a periodic action wind tunnel [12]. In experiments [13] it was revealed, that turbulization of an external flow results in a substantial growth of recirculation movement velocity in the rectangular cavity. The results of the heat exchange experiment on a surface of a sharp cone with ring dredging, with a hypersonic co-flow at Mach number, M = 6.0 are described in [14]. The supersonic turbulent co-flow around rectangular cavities with relative lengths L/D = 6, L/D = 12, 16 in presence of a thick boundary layer is investigated in [15]. Similar conditions were also studied at Mach number, M = 1,5; 2,5 [16], the pressure distribution vs relative cavity length and boundary layer thickness was considered.

The pressure distribution in a cavity is experimentally investigated at supersonic speeds and it was proposed to use passive control methods for obtaining the needed pressure distribution in a closed cavity that allows to reduce cavity resistance up to approximately three times [17]. The results of numerical simulation of cavity flow with supersonic co-flow of viscous heat-conducting compressible gas were presented in [18]. The supersonic turbulent co-flow of rectangular cavities with relative length L/D = 6 and L/D = 17.5 and width 1 and 2.5 cm accordingly [19] was numerically studied. It is shown, that the passive supply of gas to a cavity changes the geometry of a flow and transforms the closed cavity to the open one. For open cavities numerical simulations of a supersonic co-flow are carried out [20]. Heat exchange and the structure of cavity flow at the surface with a supersonic co-flow are analyzed in [21], and characteristics of a compressed boundary layer above a cavity are investigated in [22].

III. EXPERIMENTAL TEST RESULTS

Cavity flows occur in many different applications, for example, in flows around elements of aircraft and rockets, in wind tunnels, propulsion systems, etc. In comparison with the analogous experimental tests of another authors described in the previous section, in the present experimental tests, the cavity geometry and pressure sensors' locations varied simultaneously during one experiment. This capability allowed experimental results for a wide range of main parameters to be obtained by employing only the single model. A schematic of this model is shown in Figure 1.

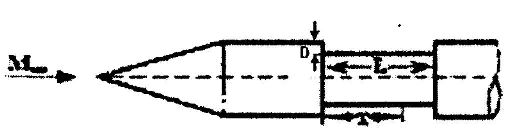


Fig. 1. The schematic of the cylindrical model with nose cone and the axisymmetric cavity tested in the supersonic wind tunnel, A-7 at the Institute of Mechanics of Moscow State University (Moscow, Russia).

The cavity length, L, and free stream Mach number, M_∞, varied in the range: L/D=0.5-14 and M_∞=0.6-3.0, where D is the reference cavity depth (the difference between the external and internal model radii).

Two Schlieren visualization types were employed in these experimental tests: with large and small exposure times. That allows an investigation of the average flow parameters as well as oscillation processes. Some previous experimental and theoretical results for cavity flows were reviewed in the report [1].

These experimental tests were conducted using the wind tunnel, A-7, at the Institute of Mechanics of Moscow State University (IM/MSU). This project was a development of the joint research between IM/MSU, NASA Glenn Research Center and the Hampton University Aeropropulsion Center under the CRDF grant, RE1-2068 and current NASA grant, NAG-3-2422. The experimentally tested axisymmetric model has a conical nose with a 9° semi-angle and a 68mm diameter cylindrical portion. The cylindrical cavity front is located at 280 mm from the transitional cross section between conical and cylindrical portions of the model. The cavity depth, D, is equal to10 mm. The pressure gauges, DMI-10-2, were installed at the cavity bottom, and the pressure gauges, IKD-27, were installed on the lateral surface of the model. The relative root-mean-square error of measured pressure by the DMI-10-2, <p>, was equal to 0.03. The measured data were transmitted to the computer complex. The moving cylindrical portion of the model can change the cavity length from 5mm to 140 mm with 10mm intervals.

The Reynolds number, Re, was calculated using turbulent boundary layer parameters at the external boundary and 1m as the characteristic length. This value was changed in the range: Re = $6x10^5$-$2x10^7$ when the free stream Mach number was changed in the range: M_∞ = 0.6-2.84. The boundary layer thickness, τ, changed in the range: τ~6-8mm (τ/D~0.6-0.8).

Below we present several experimental test results obtained during experimental research at IM/MSU supersonic wind tunnel A7. A comparison of these results with experimental results of previously done research and numerical simulation results shows very good agreement.

In Figures 2 through 14 different kinds of non-dimensional pressure distribution dependencies is shown.

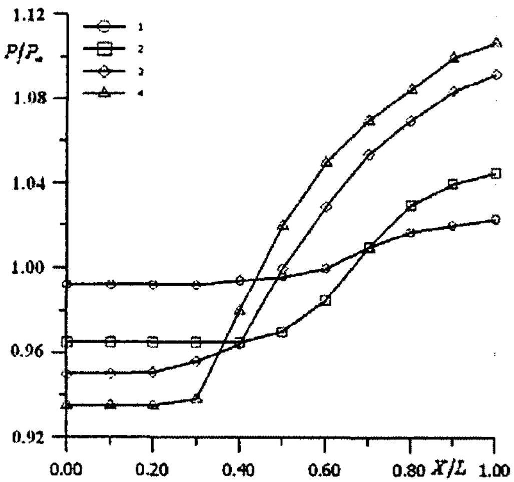


Fig. 2 Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞= 0.6: 1 - 4 - experiment, L/D = 5.3, 7.3, 9.4, 11.3.

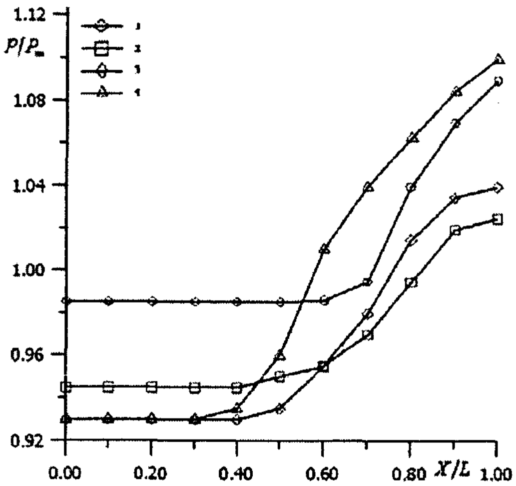


Fig. 3 Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞= 0.8: 1 - 4 - experiment, L/D = 5.3, 7.3, 9.4, 11.3

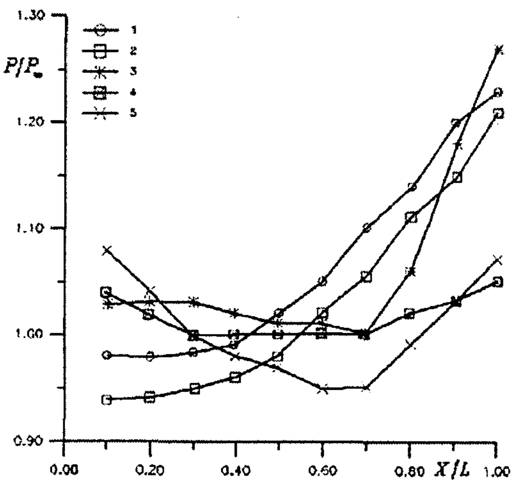


Fig. 4. Comparison of present results with result with the previous results of other authors. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞ = 1.18: 1, 2 - experiment, L/D = 5.3, 7.3; 3 numerical simulation results [19], L/D = 6, M_∞ = 1.5, Re = 6.56 10^6; 4 - experiment, [15], L/D = 6, M_∞ =1.5, Re = 6.56 10^6; 5 – numerical simulation results [15], L/D = 6. M_∞ = 1.5, Re = 6.56 10^6.

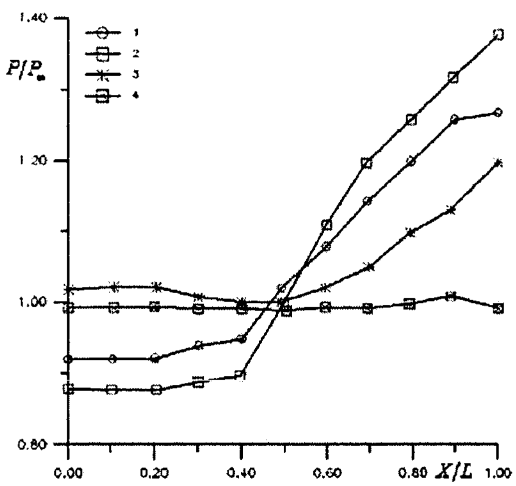


Fig. 5. Comparison of present results with previously described. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞ = 1 .18: 1, 2 - experiment, L/D = 9.4, 11.3; 3 - experiment, [16], L/D = 9, M_∞ = 1.5; 4 – numerical simulation results [18], L/D = 20, M_∞ = 1.05, Re = 10^3.

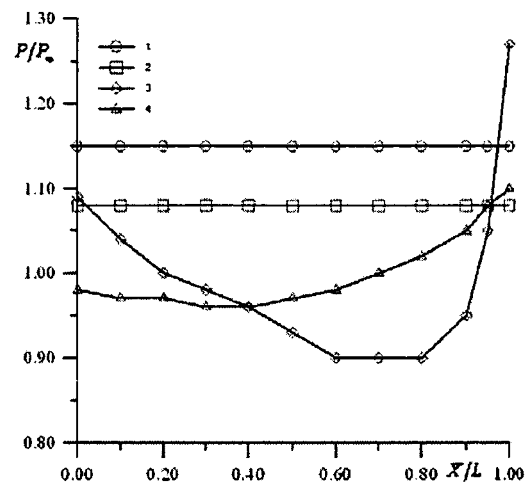


Fig. 7. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞ = 2.84: 1-3 - experiment, L/D = 0.5, 1.0, 2.0; 4 - experiment [2], L/D = 2.5, M_∞ = 2.78.

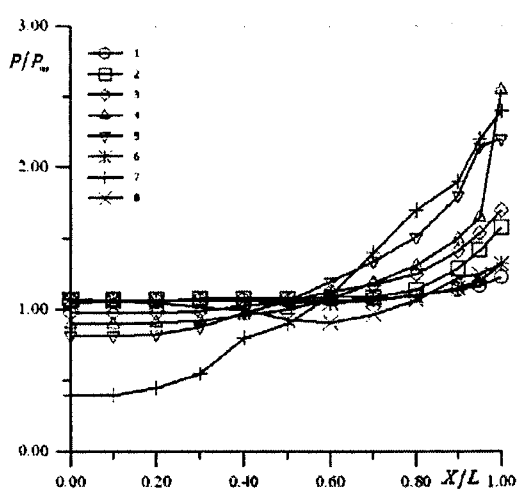


Fig. 6. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞ = 1.9 : 1 - 5 - experiment, L/D = 5.3, 7.3, 9.4, 10.4, 12.5; 6 – numerical simulation results [19], L/D = 6, M_∞ =1.5, Re = 6.5.10^6; 7 - experiment [15], L/D = 6, M = 1.5; 8 - experiment, [16], L/D = 9, M_∞ =1.5.

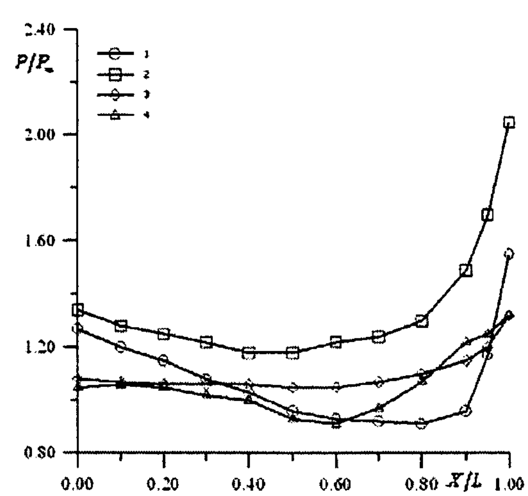


Fig. 8. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, M_∞ = 2.84: 1, 2 - experiment, L/D = 4, 6; 3 - experiment [16], L/D = 3, M_∞ = 2.5, 4 - numerical simulation results [20], L/D = 3, M_∞ = 2.5.

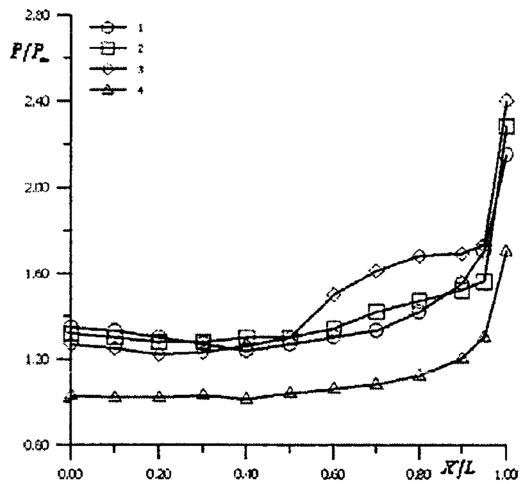


Fig. 9. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, $M_\infty = 2.84$: 1 - 3 - experiment, L/D = 8. 9, 10; 4 - experiment [16], L/D = 9, $M_\infty = 2.5$

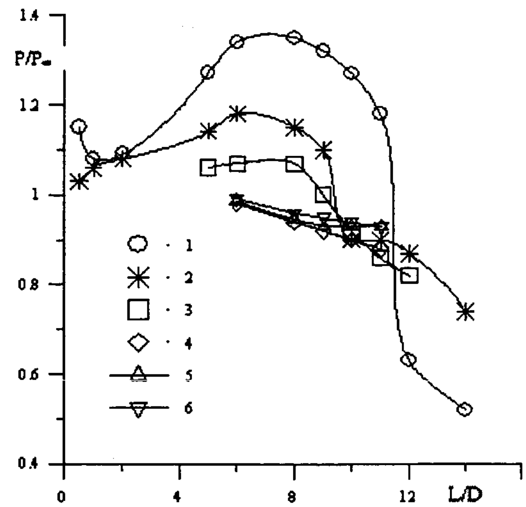


Fig. 11. Dependence of non-dimensional pressure, P/P_∞, at the front cavity point, X/L = 0, for different cavity length, L/D: 1-experimental data for $M_\infty = 2.84$; 2 – experimental data from [2] for $M_\infty = 2.78$; 3 - 6 experimental data for $M_\infty = 1.9$; 1.18; 0.8; and 0.6.

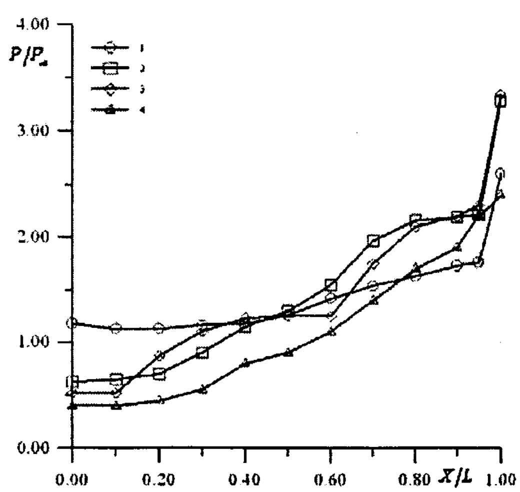


Fig. 10. Distribution of relative pressure P/P_∞ along the bottom of axisymmetric cavity at Mach number, $M_\infty = 2.84$: 1 - 3 - experiment, L/D = 11, 12, 14; 4 - experiment [2], L/D = 12, M_∞ = 2.78.

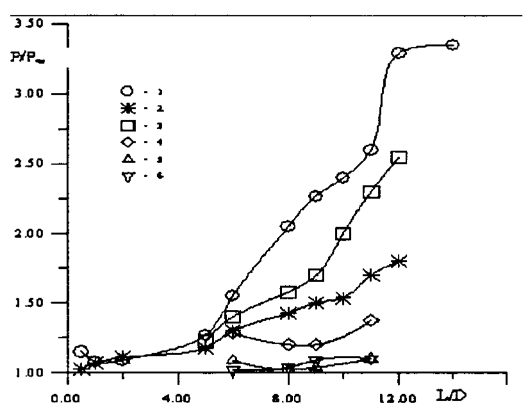


Fig. 12. Dependence of non-dimensional pressure, P/P_∞, at the rear cavity point, X/L = 1, for different cavity length, L/D: 1-experimental data for $M_\infty = 2.84$; 2 – experimental data from [2] for $M_\infty = 2.78$; 3 - 6 experimental data for $M_\infty = 1.9$; 1.18; 0.8; and 0.6.

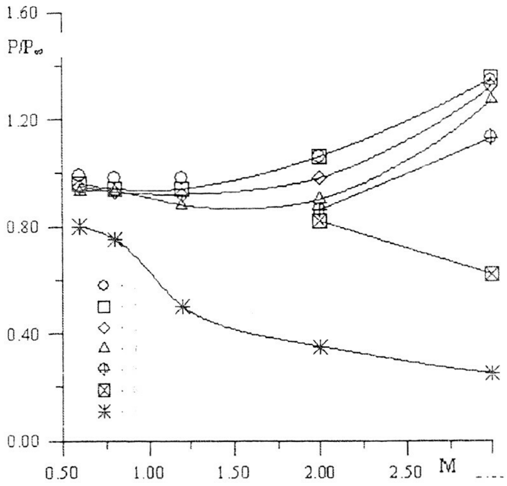


Fig. 13. Change of relative pressure P/P_∞ in the front point of a cavity (X/L = 0) vs Mach number, M: 1 - 6 - experiment, L/D = 5.3, 7.3, 9.4, 10.4, 11.3, 12.5; 7 - experiment [7], ground pressure behind a cone with angle between floor and corner θ = 7.5 °.

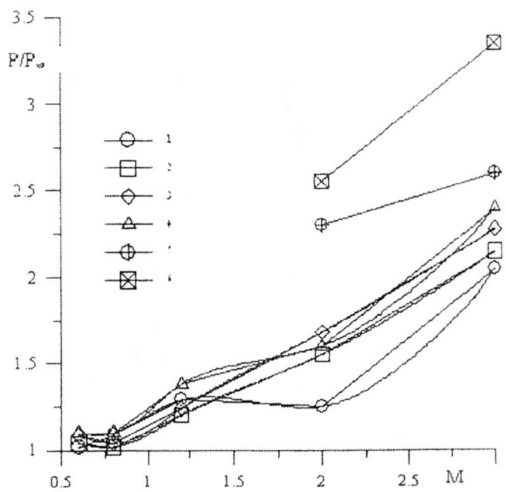
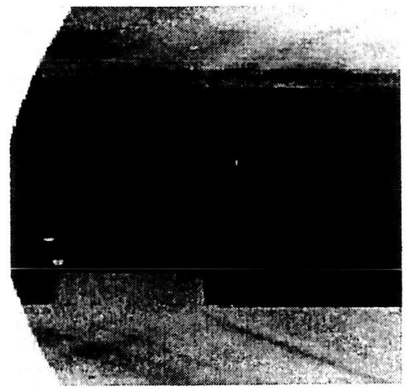


Fig. 14. Change of relative pressure P/P_∞ in a back point of a cavity (X/L = 1) vs Mach number, M; a back point (X/L = 1): 1 - 6 - L/D = 5.3, 7.3, 9.4, 10.4, 11.3, 12.5.

Dependence of flow regimes vs the cavity length and Mach number was also determined using optical measurements. In dependence on free stream Mach number and non-dimensional cavity length, there were two main regimes observed in these experimental tests: with open cavity flow (Figures 15 and 16)



a)

b)

Fig.15. Schlieren photos (a) and (b) of the open cavity flows for the cases: L/D = 4 (a) and 10 (b). Free stream Mach number is: M_∞ = 2.84.

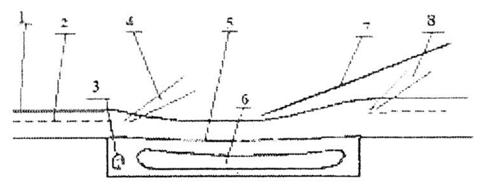


Fig.16. The schematic of open cavity flow based on experimental data shown in Figures 2 a) and b). The numbers correspond to: 1 - turbulent boundary layer; 2 - sonic line (M = 1.0); 3 - small vortex at the cavity front edge, 4 – rarefaction waves, 5 - cavity lip-line that divides the cavity internal and external flows, 6 - basic vortex flow. 7 - condensation shock; 8 – compression waves.

and with closed cavity flow (Figures 17 and 18).

Fig.17. Schlieren photo of the closed cavity flow for the case: L/D = 12. Free stream Mach number is: $M_\infty = 2.84$.

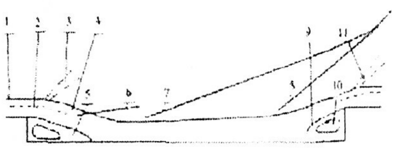


Fig.18 The schematic of closed cavity flow based on experimental data shown in Figure 4. The numbers correspond to: 1 - turbulent boundary layer; 2 - sonic line (M = 1.0); 3 - rarefaction waves; 4 – cavity lip-line of the first separation zone; first separation zone; 6 – shock wave; 7 and 8 - condensation shocks; 9- cavity lip-line of the second separation zone; 10 – second separation zone; 11- rarefaction waves.

In the case of a subsonic flow over the closed cavity, there is an interaction between two separation zones inside the cavity. These zones appeared at the cavity front and rear walls. The pressure smoothly increases from the front to rear walls. The front separation zone decreases and rear separation zone increases with increase of a free stream Mach number in the range: M_∞ = 0.6-0.8. Transition from the flow with an open separation zone to the flow with a closed separation depends on many factors: the cavity geometry, Mach and Reynolds numbers, boundary layer thickness and some others.

An analogous analysis was conducted for supersonic free stream flows. The flow structure is complicated by a presence of a shock wave system over the cavity flow. In this case, the pressure at the rear cavity wall changes non-monotonically with increase of the cavity length: it decreases in the initial interval of the cavity length and then increases. This effect grows with increasing Mach number. New experimental data were obtained for the less investigated case in which two separation zones and two shock waves were observed.

IV. CONCLUSIONS

Experimental test results of air flow inside and at the cylindrical cavity located on axisymmetric body are presented. These tests were conducted in the wind tunnel A-7 of Institute of Mechanics at Moscow State University. Pressure distribution along the cavities and optical measurements were obtained. Dependence of these characteristics of length of a cavity in the range: L/D = 0.5 - 14 and free stream Mach in the range: M_∞ = 0.6 - 3.0 was determined. Flow structure inside the cavity, cause of flow regime change, separation zones geometry and others were studied. In particular, the flow modes of with open and closed separation zones are determined. In comparison with the analogous experimental tests of another authors, in the present experimental tests, the cavity geometry and pressure sensors' locations varied simultaneously during one experiment. A comparison of these results with experimental results of previously done research and numerical simulation results shows very good agreement.

V. ACKNOWLEDGEMENTS

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